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Refinery Process Heater NOx Control by Staged Combustion Air Lances

KVB, Inc., Irvine, CA

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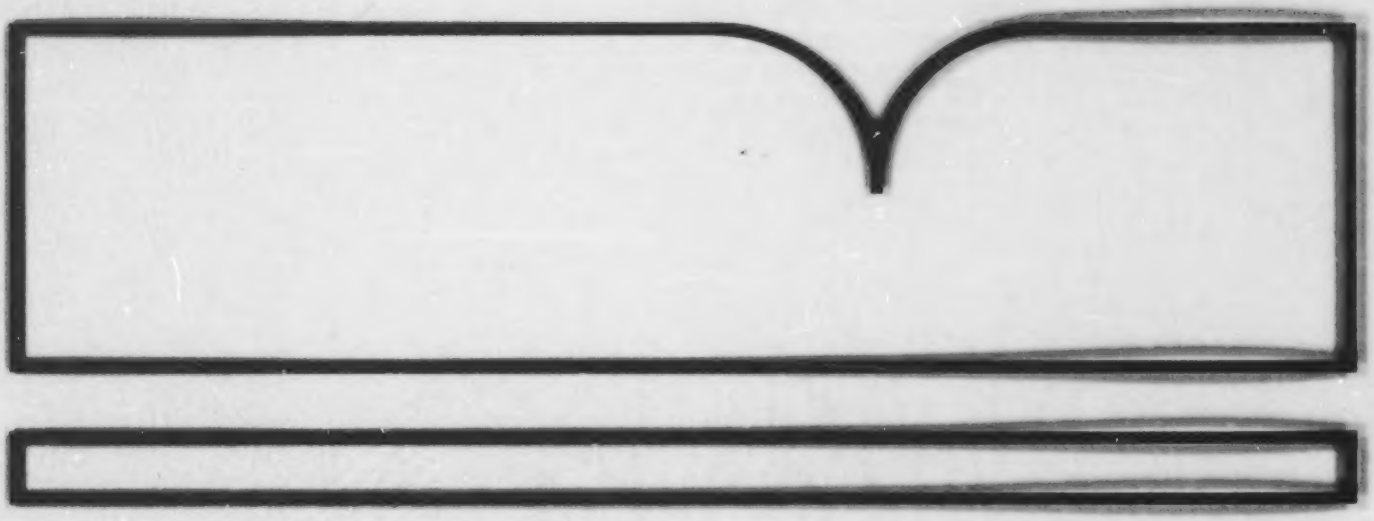

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16. ABSTRACT The paper gives results of tests of a natural-draft petroleum-refinery crude-oil process heater, modified to reduce oxides of nitrogen (NOx) emissions by installing staged-combustion air lances. Baseline nitric oxide (NO) emissions firing refinery gas before modification were measured to be 100-125 ppm by volume, dry, corrected to 3% oxygen. Staged-combustion air lances bypassed combustion air around the burners to achieve staged combustion. With the modification, an average reduction of 64% in NO emissions was observed over a 30-day test period, with NO emissions of 25-50 ppm, depending on the excess air.

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Control	Staged Combustion	11H, 08G
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Refinery Process Heater NO_x Control by Staged Combustion Air Lances

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A vertically fired natural-draft petroleum-refinery crude-oil process heater was modified to reduce oxides of nitrogen (NO_x) emissions by installing staged combustion air lances. Baseline NO emissions firing refinery gas before modification were measured to be 100 to 125 parts per million by volume, dry, corrected to 3 percent oxygen. Staged combustion air lances were installed to bypass combustion air around the burners to achieve staged combustion. With the modification, an average reduction of 64 percent in NO emissions was observed over a 30-day test period, with NO emissions of 25 to 50 ppm, dependent on the excess air. This method of combustion modification can be applied to most vertically fired process heaters where flame length increased by a factor of 2 to 4 would not cause flame impingement.

Introduction

Emissions of oxides of nitrogen (NO_x) from petroleum industry stationary sources are estimated (Hunter and Cherry, 1979) to be about 1,300,000 tons (1,201,000 metric tons) per year based on 1975 data. This emission rate is about 6 percent of the total stationary and mobile NO_x emissions from all sources in the United States. Petroleum refining operations produce 22 percent of total petroleum industry NO_x emissions. Natural draft process heaters are the prevalent source of NO_x in refineries, contributing about 10 percent of total petroleum industry NO_x emissions.

There are currently no New Source Performance Standards for NO_x from petroleum process heaters. However, the U.S. Environmental Protection Agency regularly reviews the NSPS for refineries and has a need to understand the potential for controlling process heater NO_x emissions. In the State of California the South Coast Air Quality Management District has adopted limitations on NO_x emissions from petroleum refineries, and other areas of the U.S impose limits, including new source review requirements for Best Available Control Technology. These various needs have resulted in research to investigate NO_x controls for process heaters.

This paper summarizes research conducted under contract to the Combustion Research Branch at the U.S. Environmental Protection Agency's Air and Energy Engineering Research Laboratory in Research Triangle Park, NC. Research involving evaluation of combustion modifications on a variety of industrial process combustion equipment was performed under this contract. This paper concentrates on the process heater portions of the research, summarizing results that have been reported in detail (Tidona et al., 1983).

Petroleum Refinery Process Heater Characteristics

Process heaters are of two basic types: natural draft and mechanical draft (forced, induced, or balanced draft). These draft types result in basic differences in combustion characteristics that are reflected in NO_x emission levels and feasibility of combustion modification. Some mechanical draft units are equipped with combustion air preheating that, in general, is expected to increase NO_x emissions because of higher flame temperatures. There are two basic forms of heater construction: horizontal box and vertical cylindrical. Horizontal tubes are most common in box heaters, but some have vertical tubes. Burners are usually mounted in the floor firing upward, but may also be located in the side. Box units can have from 3 to over 100 burners arranged in one or more rows. Two or more box furnaces may be connected to a single convection section. Vertical-cylindrical units all have vertical tubes, and one or more burners are mounted in the floor firing upward.

The refining process performed is important. Uniformity in heat distribution required varies with process type, and this influences the flexibility of the combustion system. Process heater tests reported here encompass only one process: crude oil heating. The heater made available for testing did not involve the most critical processes where the unknown effects of combustion modifications might result in process disruption or heater damage, primarily product tube internal coke formation.

These details are important in application of combustion modifications because process heater construction differs from that of steam boilers. Burners for heaters also differ from steam boiler burners. Heater burners form round, conical, or flat flames to produce the proper heat distribution necessary to avoid tube coking, which is not a problem in steam boilers. These differences imply that combustion modifications developed on steam boilers, and reductions in NO_x achieved, may not be directly applicable to process

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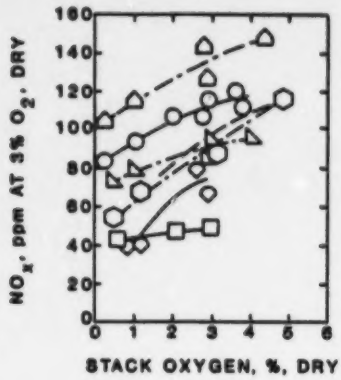

BURNER TYPE	BURNER MODIFICATION
△ DBA-16	NONE, BASELINE
○ MA-16	NONE, BASELINE
◺ DBA-16	ROTATED GAS TIPS
⬡ DBA-16	STAGED AIR, CENTRAL CYLINDER
◇ MA-16	STAGED AIR, 4 LANCES
□ MA-16	FLUE GAS RECIRCULATION

Fig. 1 Summary of NO_x emissions as a function of stack oxygen for subscale natural-draft furnace firing natural gas

heaters. Therefore, specific research is necessary to tailor these techniques to process heaters.

Combustion Modifications on a Subscale Research Heater

Prior to attempting hardware modifications on a refinery heater, several potential modifications were evaluated in a subscale research furnace at the factory of a major manufacturer of process heater burners. The furnace was a refractory lined, uncooled, rectangular, box-type furnace 8 ft (2.4 m) wide by 6 ft (1.8 m) deep by 32 ft (9.8 m) high.

A single natural-draft burner was installed in the furnace floor firing vertically upward. The nominal firing rate for the tests was 5×10^6 Btu/hr (1.5 MW). Furnace draft was controlled manually with a damper in the stack. View ports were provided for observing flame shape.

The furnace had the capability of firing either oil or natural gas. Both flows were measured with flowmeters. Thermocouples were installed in the side of the furnace to measure the vertical thermal gradient and the temperature/time behavior during furnace heat-up.

The modifications evaluated included:

1 Lowered excess air
2 Redesigned burners (low-NO_x burners)
3 Flue gas recirculation
4 Steam injection
5 Altered fuel injection geometry
6 Staged combustion air lances

The results obtained have been reported previously in detail (Hunter et al., 1979). Figure 1 shows the NO_x emissions for the various modifications as a function of stack oxygen while firing natural gas. At low stack oxygen levels (1 percent), flue gas recirculation and staged combustion air lances both produced similar reductions. At higher stack oxygen levels, flue gas recirculation was superior to staged combustion air lances, showing less sensitivity to variation of excess air.

An analysis of cost/effectiveness ratio, expressed as annual cost per unit mass of NO_x (as NO_2) reduced, indicated that staged combustion air lances had a significantly lower cost/effectiveness ratio compared with flue gas recirculation. Therefore, the staged combustion air lance method was selected for installation in an operating refinery process heater as discussed below. Based on the research furnace tests, a reduction in NO_x of 40 to 67 percent was anticipated for a pilot-scale system firing gas fuel.

Pilot-Scale Test Heater

The pilot-scale test unit was a natural draft, vertical-cylindrical crude-oil process heater, which is used to supply a partially vaporized charge to a crude oil distillation column. A maximum load of 16,250 bbl/d (108 m^3/h) can be sent through the heater in two passes. The maximum firing rate of the heater is 55×10^6 Btu/hr (16.1 MW) thermal input. It is fired by six natural-draft DBA-type burners arranged in a circle in the heater floor. The burners are combination gas/oil burners rated at a maximum of 9.14×10^6 Btu/hr (2.68 MW) each with a turndown ratio of 3:1.Although combination gas/oil burners are used, some gas must always be fired because the unit is base loaded at constant oil firing rate, and an automatic temperature controller adjusts the gas fuel flow to maintain crude oil outlet temperature.

Staged Combustion Air Lance System Description

A staged combustion air lance system flow schematic is presented in Fig. 2. The purpose of the system is to bypass a portion of the combustion air around the burners and inject the air into the flame above the fuel injection plane of each burner. The air is injected into the firebox through tubular lances, which penetrate through the floor of a vertically fired unit. The introduction of air above the burners permits fuel-rich operation at the burners with as little as 50 percent of the theoretical air required for complete combustion, achieved by closing the burner air registers. The combustion air injected through the lances provides the remainder of the theoretical air requirement plus the amount of excess air necessary to eliminate combustibles in the flue gas and provide a good flame.

A prototype system was constructed of polyvinylchloride pipe, fittings, and valves, connected through flexible tubing to 24 stainless steel lances made from 3.2 cm (1.25 in.) 316 stainless tubing. The lances were arranged on a 3-ft (1-m) diameter around each burner, four lances per burner at 90 degrees, two lances on the burner centerline circumference and two on each burner radial line. The system was designed to provide flexibility for the adjustment and control of air flow, including the capability to control the lance air flow to each burner by means of ball valves. The lance height above the furnace floor was adjustable from floor level up to 8 ft (2.4m) above the floor. The ability to adjust flows and lance position, although desirable for testing, should not be necessary in a permanent system.

Emissions Sampling Instrumentation

The gaseous and particulate emissions were monitored with an EPA-furnished mobile laboratory. Continuous gaseous emissions analyzers measure volumetric concentrations of O_2, CO_2, CO, SO_2, NO, NO_x, and HC (as methane) in the flue gas. Particulate total mass and size were measured. SO_3 measurement was by a controlled condensation technique using a Goksoyr-Ross type coil. The sampling system and test methods are discussed in detail in the final project report (Tidona et al., 1983). All NO and CO emissions discussed in this paper are expressed in parts per million (ppm) by volume,

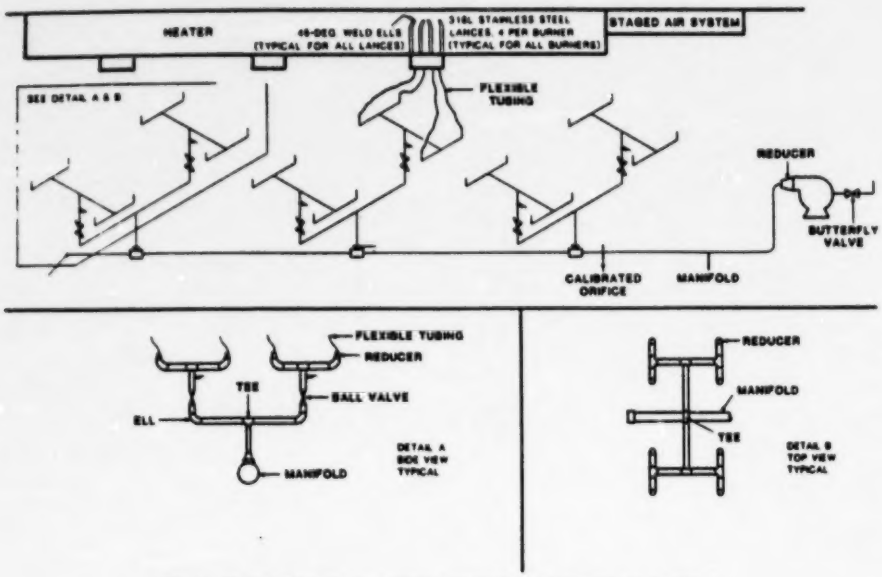

Fig. 2 Flow schematic of staged combustion air system for a natural-draft process heater

dry basis, corrected to 3 percent oxygen. Only NO data are presented. NO_2 was found to be from 0 to 10 ppm, with an average value of 3 ppm, which is below the accuracy of the measurement method.

Staged Combustion Air Lance Testing

Evaluation of the staged combustion air system included the variation of three important parameters: (1) burner theoretical air ratio, (2) stack oxygen level, and (3) staged air lance insertion height.

The NO emission is graphed as a function of burner theoretical air ratio in Fig. 3. The staging height for this test series was 4 ft (1.2 m) and the load was 9600 bbl/d (64 m^3/h), 60 percent of rated capacity. At each overall stack O_2 level, burner air was decreased in steps to a minimum value determined by the limitations of the staged combustion air fan. At 4 percent O_2, the minimum burner theoretical air ratio (maximum staging) was 0.74, which decreased NO emissions 35 percent below the baseline of 105 ppm. At 2 percent O_2 and burner theoretical air ratio of 0.65, the NO concentration dropped to 51 ppm. This represented a reduction of 51 percent below the 4 percent O_2 baseline condition and a reduction of 43 percent below the 2 percent O_2 level with no staged air. These results generally confirmed the research furnace tests using a single burner, indicating little influence of a multiple burner arrangement.

Staging the combustion air while firing a mixture of No. 6 oil and adsorber gas at intermediate load did not produce as large a percentage decrease in NO emissions as when firing adsorber gas only. The absolute amount of NO concentration reduction, however, was about the same with combined fuel firing as it was with gas alone. For example, the NO level firing oil decreased from a baseline of 219 ppm to 166 ppm, a reduction of 53 ppm. Firing adsorber gas, the reduction was 46 ppm. This indicates that fuel oil nitrogen conversion to NO was responsible for approximately half of the baseline NO emission firing oil with gas, and the other half was due to thermal NO formation. The estimated fuel nitrogen conversion efficiency is approximately 19 percent, based on the ratio of oil to gas in the fuel and the fuel nitrogen content (~0.8 percent) of the oil.

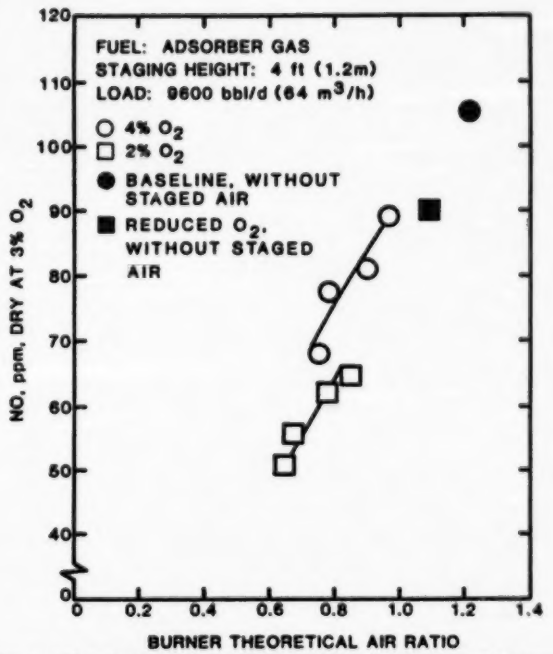

Fig. 3 NO emissions as a function of burner equivalence ratio at two stack oxygen levels with constant staged air insertion height

NO emissions decreased slightly as staging height was increased while firing oil together with gas. However, very little decrease was observed at heights greater than 4 ft (1.2 m).

During all testing, the flame and furnace draft were observed carefully. There did not appear to be any problems with coking of the process tubes and at no time was there any measurable emission of CO or unburned HC, even at 2 percent stack oxygen. In certain instances, the draft in the convection section became slightly positive at the low O_2 condition with maximum staging; however, flashback was never observed. A general lengthening of the flame was observed, in-

Table 1 Summary of 24-hr average gaseous emissions data

Petroleum Process Heater, Staged Combustion Air, Refinery Gas Fuel
24-Hour Data
Dry Stack Gas Concentration

Date	Load B/D	O_2 Vol % Meas.	CO_2 Vol % Meas.	CO ppmv 3% O_2	NO ppmv 3% O_2	CO ng/J	NO ng/J
5/01/81	10717.0	1.6	12.3	7	32	2	17
5/02/81	10717.0	2.1	12.0	10	40	3	22
5/03/81	10717.0	2.3	11.9	10	43	3	23
5/04/81	10717.0	2.2	11.9	12	42	4	22
5/05/81	10717.0	2.3	11.9	26	40	8	21
5/06/81	10717.0	2.5	11.7	8	42	2	23
5/07/81	10717.0	2.7	11.6	27	42	9	22
5/08/81	10717.0	2.2	11.9	5	37	1	20
5/09/81	10717.0	1.9	11.8	12	33	4	18
5/10/81	10717.0	1.6	12.3	12	29	3	16
5/11/81	11178.7	1.6	12.3	39	29	13	16
5/12/81	10717.0	1.4	12.4	8	27	2	14
5/13/81	10717.0	1.7	12.2	4	29	1	16
5/14/81	10717.0	1.6	12.2	11	30	3	16
5/15/81	10717.0	1.6	12.1	11	29	3	16
5/16/81	10717.0	3.9	10.5	73	57	24	31
5/17/81	10717.0	6.8	8.9	8	100	2	54
5/18/81	10717.0	3.6	10.8	216	49	71	26
5/19/81	10717.0	3.3	10.8	96	49	31	27
5/20/81	10717.0	1.6	11.9	51	28	16	15
5/21/81	10717.0	2.4	11.7	10	34	3	18
5/22/81	10717.0	2.5	11.7	46	34	15	18
5/23/81	10717.0	4.4	10.5	21	54	7	29
5/24/81	10717.0	2.1	12.0	19	41	6	22
5/25/81	10717.0	3.3	11.3	99	43	32	23
5/26/81	10717.0	4.2	10.7	7	48	2	26
5/27/81	10717.0	4.2	10.6	8	48	2	26
5/28/81	10717.0	4.1	10.4	5	49	1	26
5/29/81	10717.0	3.8	10.8	10	53	3	28
5/30/81	10717.0	3.9	10.8	13	51	4	27
5/31/81	10717.0	3.9	10.8	12	47	4	25
6/01/81	10717.0	3.7	10.8	8	46	2	25
6/02/81	10717.0	3.9	10.6	6	48	2	26

Table 2 Cost/effectiveness ratio ($/Mg) of combustion modification applied to three natural draft process heater sizes

Modification	Heater Size* 16.1 MW	29.3 MW	147 MW
Staged Combustion Air at 4% O_2	2636**	2362	1934
Staged Combustion Air + Lowered Excess Air (2% O_2)	1089	700	(40)
Lowered Excess Air, Firing Gas	(5843)	(6853)	(4813)
Lowered Excess Air, Firing Oil and Gas	(1459)	(1712)	(2189)

* 10^6 Btu/hr = MW x 3.42
** $/ton = $/Mg x 0.907
( ) indicates cost savings

creasing by a factor of 2 to 4, but this did not result in flame impingement on the internal surfaces.

Extended Duration Test of Staged Combustion Air Lance System

An endurance test was conducted while firing refinery gas to evaluate the staged air lance system during normal refinery operations. The objective of the test was to collect data continuously for 30 days. The actual test period was 33 days. The load was constant at 10,717 bbl/day (71 m^3/h) throughout the test, except for one upset day.

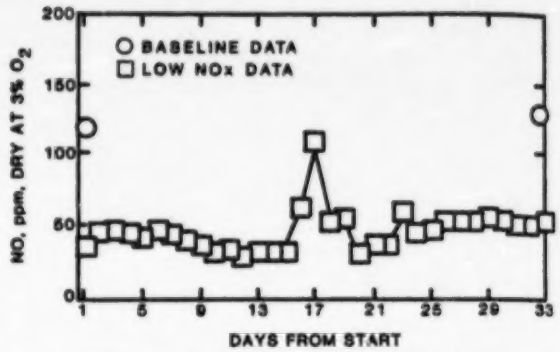

Fig. 4 NO_x emissions variation during 30-day test

A mobile laboratory was used to measure the gaseous emissions. The monitoring system was certified in accordance with Performance Specifications 2 (PS2) and 3(PS3) of 40 CFR 60. These specifications establish minimum performance that the NO monitoring system must meet in terms of eight parameters: accuracy, calibration error, 2- and 24-h zero drifts, 2- and 24-h calibration drifts, response time, and operational period.

Gaseous emissions data were measured continuously and recorded on an automatic data logger, strip chart recorders, and a magnetic tape recorder. Fifteen-minute averages of NO, O_2, CO_2, and CO emissions were recorded on tape. The data were processed on a computer, and 15-min averages were compiled. These data were then used to compile 24-h averages for the entire test period. The 24-h averages compiled from the 15-min averages for the 30-day test period are summarized in Table 1, showing O_2 and CO_2 as measured, CO and NO corrected to 3 percent O_2, and CO and NO expressed in ng/J using the gaseous fuel sample analyses.

Baseline emissions with no staged air were measured before and after the 30-day test. The NO emissions before and after the test were 120 and 130 ppm, dry, corrected to 3 percent O_2, respectively. On a heat input basis, the baseline emissions were 0.144 and 0.156 lb/10^6 Btu (62 and 67 ng/J), respectively.

After conducting baseline tests, the staged air system was activated and the stack oxygen was lowered to approximately 2 percent with the concurrence of the refinery operating personnel. The heater was then operated in this mode steadily for 15 days. After approximately 15 days, a change in the crude oil charge required an increase in firing rate. Since the heater was not controlled automatically, the increase in fuel flow resulted in a deficiency in oxygen and high CO values. The operators responded by opening the dampers, resulting in high values of stack oxygen. The highest 24-h average CO emission rate was 216 ppm, dry, corrected to 3 percent O_2 (71 ng/J). On the other 32 days, CO averaged 22 ppm and never exceeded 100 ppm, as shown in Table 1. Peak values of CO were approximately 1300 ppm.

The day following the crude oil change, efforts were made to reduce O_2 to the previous 2 percent level. Due to changing conditions and lack of automatic controls, it was decided to operate the remainder of the test at about 4 percent oxygen.

The NO emission rate as a function of days from the start of testing is presented in Fig. 4. The peak occurred during the upset condition when O_2 was increased. Even under the high O_2 condition, with the staged air system operating, the NO emission rate was lower than the baseline level. The NO emission rate data were divided into two groups corresponding to 2 and 4 percent stack oxygen. The mean value of NO emission

for the 2 percent O_2 setting was 35 ppm, and the mean value for the 4 percent O_2 setting was 49 ppm.

The results of this test, relative to the average baseline NO emission of 125 ppm, were 60 percent reduction at 4 percent O_2, 71 percent reduction at 2 percent O_2, and an overall average NO reduction of 64 percent. Upon completion of the tests, inspection of the staged air lances did not reveal any corrosion or damage to the lance material.

The cost/effectiveness ratio, based on a permanent system, of the staged combustion modification was evaluated for the gaseous fuel and for combination fuel, and also at two levels of stack oxygen. Cost/effectiveness ratio is defined as the total annual cost, including capital charges and operating costs, divided by the annual reduction of NO_x, expressed as dollars/megagram (dollars per ton). The cost/effectiveness ratios are shown in Table 2 for three heater sizes. The values for low excess air and for staged combustion with low excess air on the largest heater are negative, indicating a cost savings in addition to an NO reduction. This is a desirable situation; however, one must realize that a modification that saves money yet produces only a small NO reduction will have a large negative cost/effectiveness ratio. This may not be the most desirable modification if the NO reduction is less than is necessary to achieve compliance with regulations or to offset future emissions from plant expansions.

Guideline Manual

A manual (Tidona, 1983) has been prepared, documenting the procedures for implementing process heater combustion modifications investigated in this program. The manual is intended for use by heater manufacturers and operators.

Conclusions

On the basis of the work reported, it was concluded that:

- Based on research furnace tests with a single burner, staged combustion air injection and flue gas recirculation appear to be the most promising combustion modifications for reduction of gas-fired process-heater NO emissions, with a potential of up to 67 percent reduction.
- Installation of staged air lances through the floor of a vertically fired process heater appears to be a lower cost approach, compared with burner replacement or flue gas recirculation.
- Staged combustion using air lances was accomplished with no apparent detrimental effect on heater performance or structural integrity.
- Parametric test results with staged air lances firing gas fuel reduced NO emissions by 35 to 51 percent from a baseline level of 105 ppm, dry, corrected to 3 percent O_2.
- Test results with staged air lances firing combined No. 2 oil and gas reduced NO emissions by 24 percent from the baseline level of 219 ppm, dry, corrected to 3 percent O_2.
- NO emissions firing No. 2 oil and gas were higher than from gas alone due to oil nitrogen content of 0.8 percent by weight, indicating that about 19 percent of the oil nitrogen was converted to NO.
- Staged air lances produced about the same absolute reduction in NO concentration (about 50 ppm) while firing gas alone or combined No. 2 oil and gas.
- During an extended 30-day test of staged combustion air lances, while firing gas fuel, NO was reduced an average of 64 percent from a baseline of 125 ppm, dry, corrected to 3 percent O_2.
- Based on an examination of many process heaters in refineries, the staged air lance system should be applicable to most vertically fired heaters. The exceptions are heaters where the flames are already near the internal surfaces, in which cases lengthened flames could result in flame impingement.

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